



Proton structure in proton-antiproton collisions

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Proton-antiproton collisions at the Fermilab Tevatron collider currently offer the highest energy collisions available in the laboratory. In this paper we briefly discuss measurements which are sensitive to the internal structure of the proton. We also describe measurements which search for substructure in the partons, the quarks and gluons which form the proton.

Keywords:

1. Introduction

The description (Taylor 2000, Altarelli 2000) of the proton (and antiproton) as an ensemble of partons, quarks and gluons, naturally led to the parton-model description of hadron interactions as a sum of all possible parton interactions. Any particular scattering process is described (Ellis, Stirling & Webber 1996) as the convolution of the initial parton distributions with the relevant parton-parton cross section. Hadron collisions are therefore sensitive (Stirling 2000) to both the nucleon structure, as expressed in the parton distribution functions, and to the details of the parton interactions. By making a number of different measurements, the sensitivity to one or other, or to particular ranges of the fractional momentum of the partons, can be varied.

In this paper we discuss some recent measurements at the Fermilab Tevatron Collider which demonstrate this physics program. In Section 2, we briefly mention the experiments. In section 3, we describe measurements using jets observed in the final state. Leaving measurements with vector bosons, photons, W bosons and Z bosons to Stirling (2000), we discuss measurements of heavy quark production section 4 and parton substructure in section 5. In section 6, we summarize. We have made a personal choice of topics and emphasis, and the treatment is far from exhaustive. For example, due to limitations of time and space we have omitted a discussion of diffractive and soft collisions. A discussion of a measurement (DØ Collaboration 2000a), which is potentially sensitive to BFKL (Lipatov 1976) effects, was discussed by Foster (2000). A rather complete description, of all except the most recent developments, was given by Womersley (1999).

2. The Experiments

Hadron scattering experiments with results discussed in the context of the parton model have been performed at the Super Proton Synchrotron at CERN and at the Tevatron at Fermilab using fixed target techniques, and at the Intersecting Storage Rings and the Super Proton-antiproton Synchrotron, both at CERN, using colliding beam techniques. The two experiments relevant to this paper are the

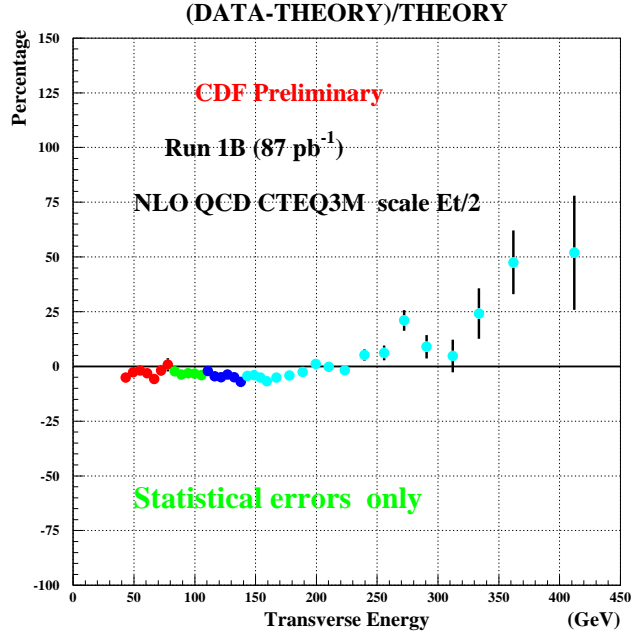


Figure 1. CDF measurement of the inclusive jet spectrum compared to the theoretical prediction using the CTEQ3M structure functions.

Collider Detector Facility(CDF) and the DØ experiments at the Fermilab Tevatron proton-antiproton collider. With these two general purpose detectors in place, the Tevatron was operated from 1992 to 1996 primarily with 900 GeV in each beam for a center of mass energy of 1800 GeV but with a small amount of data taken with 630 GeV in the center of mass.

The CDF (2000a) detector was dominated by a large volume, central, solenoidal tracker with central drift chamber and silicon vertex detector. The tracker was enclosed by a lead/steel calorimeter with scintillating tiles as the sensitive medium and using wave-shifting readout. Outside the calorimeter was a muon detection system.

The DØ (2000b) detector had a modest tracking volume without magnetic field. The prominent feature of the detector was a large liquid argon calorimeter consisting of three cryostats forming a central and two end calorimeters. The muon system consisted of large steel toroids with proportional drift tube detectors.

Both detectors are undergoing extensive upgrades at the present time in anticipation of running in 2001 with much increased luminosity, hence the past tense in the above descriptions

3. Jet Physics

A classical measurement in collider physics is that of the inclusive jet cross section. A measurement with a p_T range extending to 450 GeV was made by CDF (1996); the data compared to a prediction using the CTEQ3M parton distribution functions

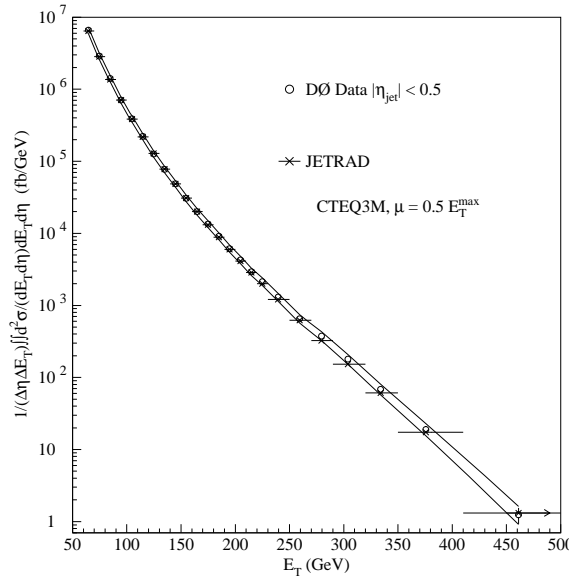


Figure 2. DØ inclusive jets cross section and a comparison with a next-to-leading order QCD prediction.

are displayed in Fig. 1. A rise at high p_T is observed. However we should note that the actual cross sections fall by about seven orders of magnitude across this plot. This is illustrated by the equivalent DØ (1999a) data which are shown in Fig. 2. In the events at high p_T the partons participating are carrying about 50% of the nucleon momentum. This is quite a high percentage even for the deep inelastic measurements in fixed target experiments and is very high for the HERA experiments. Consequently it proved possible to accommodate excursions of the magnitude seen in the CDF data by slight modifications of the parton distributions, in particular that of the gluon. The actual distribution used to illustrate this was not particularly attractive for the theoretically aesthetic, nevertheless they were not excluded by the deep inelastic data. In fact, the DØ data show no such deviation even when plotted in the same way as those from CDF. The steeply falling distributions, along with jet energy scale calibrations with uncertainties of the order of a couple of percent, produce systematic uncertainties in both measurements. Thus, despite the visual differences, the two measurements are not incompatible.

If one wishes to emphasize high or low x regions it is possible to look in regions of large rapidity (or pseudo-rapidity, η). Measurements exist for $\eta \leq 3$ and which encompass the range $0.1 \leq x \leq 0.8$. The largest range is obtained by looking, as a function of p_T , at the data in which both jets have very similar rapidity. This is the topology, with both jets on the same side of the event, which corresponds to the biggest imbalance between the fractional momenta carried by the two initial-state partons. Some measurements (CDF Collaboration 1999) are illustrated in Fig. 3 in which one jet is fixed with $\eta \sim 0$ and the other is chosen to be in one of four pseudorapidity ranges. Good agreement is seen between the data and the next-to-leading order QCD predictions.

Within the parton model, the invariant cross sections, scaled by p_T^4 , at two

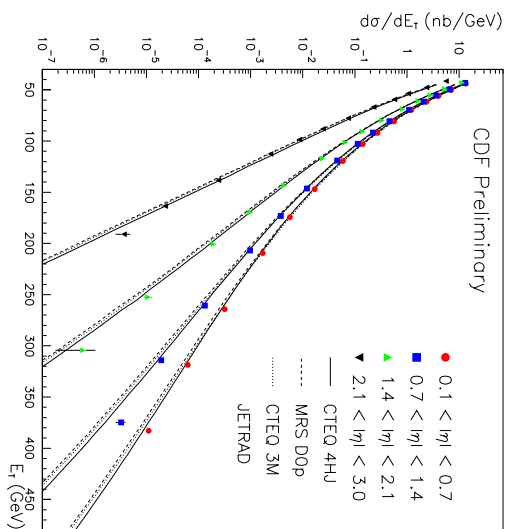


Figure 3. The CDF triple differential jet cross section measurement compared to next-to-leading order QCD predictions using a variety of different parton distribution functions.

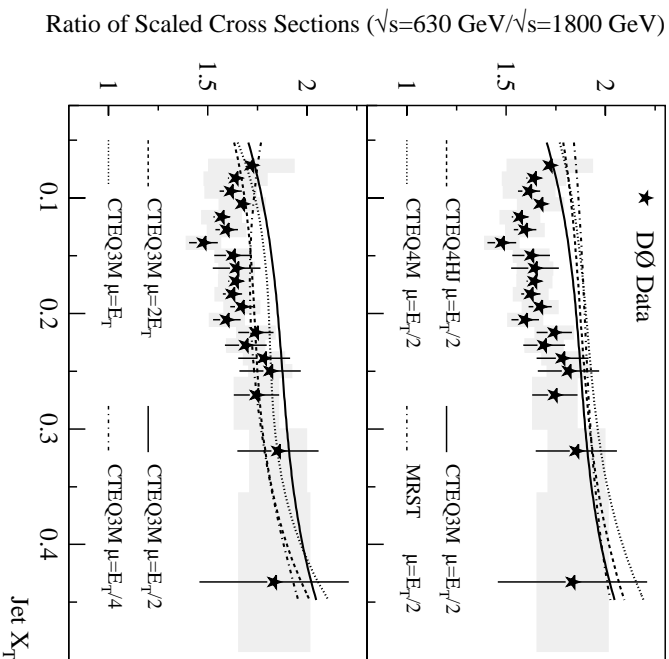


Figure 4. The ratio of cross sections at 630 GeV and 1800 GeV as a function of the scaled transverse variable x_T as measured by DØ.

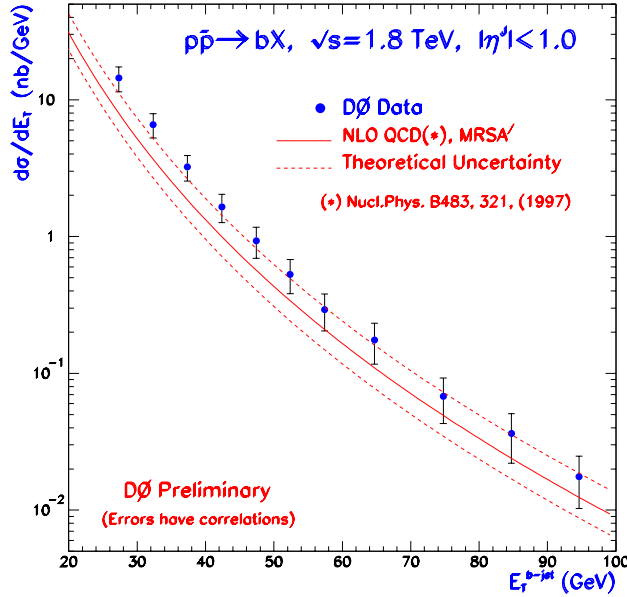


Figure 5. The b -quark jet cross section as a function of p_T as measured in the DØ experiment.

different center of mass energies, should be equal if plotted against the variable $x_T = (p_T/\sqrt{s})$. In QCD we expect to see differences as a result of the running of the strong coupling constant, and as a result of scale breaking evolution of the parton distribution functions. Thus, with similar parton distributions in the numerator and in the denominator, the differences between predictions should be reduced. This means that, by using the ratio, we can hope to remove the nucleon structure effects and study the hard interaction. A measurement from DØ (2000c) shows that the 630 GeV cross section is higher by a factor 1.6 – 1.85 and has a rather mild p_T dependence. This is shown in Fig. 4. The theory predictions are in moderately good agreement. As hoped, they are relatively insensitive to the choice of parton distribution function, as we expected and are also insensitive to the choice of s -scale variable. The agreement with the data suggests that the next-to-leading order QCD calculation of the underlying scattering cross section is good to about 20%. The equivalent CDF measurements are also in broad agreement although small deviations can be found in some x_T regions.

4. Heavy Quark Production

It is usually argued that the heavier is the quark, involved in an interaction, the easier it is to justify the use of perturbative QCD. Hence we expect more reliable predictions for the bottom- and top-quark production at the Tevatron, which should be well described by the theory. This is certainly the case for the top quark for which the total cross section has been measured. CDF (1999b) obtains $6.4 \pm {}^{1.5}_{1.3}$ pb, DØ

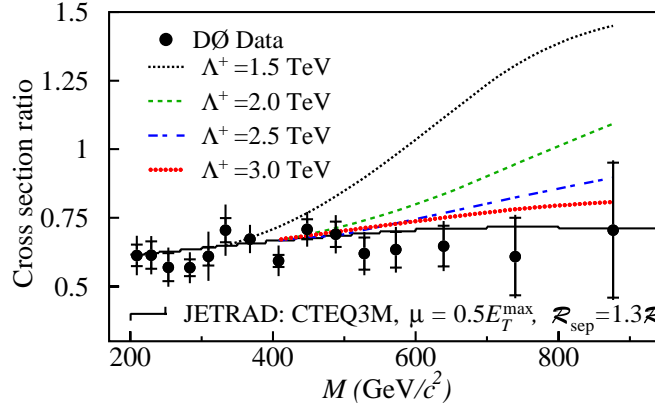


Figure 6. Ratio between the dijet cross section in two different rapidity regions as a function of the dijet mass, as measured by DØ.

(1999b) obtains 5.9 ± 1.7 pb. The theoretical predictions vary between about 5 pb and 7 pb depending on the details of the calculation. This is very good agreement.

The b -quark production cross section has been measured in the central region by both CDF and DØ and in the high rapidity region by DØ. In the central region the measurements lie above the predictions by about a factor two; the p_T range of the measurements extends to about 40 GeV. In the forward region the data are as much as a factor four higher than the theory and the p_T range extends to about 20 GeV. This situation is in stark contrast to that with the top quark. DØ (2000d) recently completed a new analysis with a different data set, which extends the p_T range. The measurement also used a different approach; it keyed on the b -jets and used a soft lepton to tag the jets rather than relying on the measurement of the decay muon. These measurements are sensitive to different systematic uncertainties, in particular they are less sensitive to fragmentation. Extending from $p_T \simeq 30$ GeV to $p_T \simeq 100$ GeV, they are also higher than the theory at low p_T but approach the predictions as p_T increases. The data have also been analysed in the same manner as the previous DØ results and a good agreement is found in the overlap region.

These data therefore suggest that while the theory appears to be inadequate at low p_T , perhaps as p_T increases the perturbative calculation at next-to-leading order in QCD might saturate the measurement.

5. Parton Substructure

The primary thrust of this meeting has been an examination of the substructure of the nucleon, the ways the substructure has been probed by experiment and described by theory. The experiments are also sensitive to possible substructure of the partons themselves. Even if the mass scale of the substructure is much above the center of mass energy of the experiments, the presence of that structure can modify the angular distribution observed. The higher scale interaction generates an effective structure different from that of the parton interactions.

The DØ (1999c) experiment exploited this feature by measuring the ratio of cross sections in two different pseudorapidity ranges as a function of the effective mass of the dijet system. Taking this ratio also exploits some cancellation of ex-

perimental systematic uncertainties. The result is shown in Fig. 6. The theoretical predictions for effective scales of 1.5 TeV through 3.0 TeV are also shown. The pure QCD prediction corresponds to a scale of infinity. We see that the data are well described by the QCD prediction and manifestly do not support any effective scale for substructure less than about 3 TeV. A more sophisticated examination, which also looks at different helicity structures of the interaction, excludes structure with a scale less than about 2.5 TeV.

Should there be constituents in common for the leptons and the partons, similar measurements with lepton pairs in the final state are sensitive in a way similar to the dijet measurements. Both CDF (1997) and DØ (1999d) have made measurements of these processes and the compositeness scale limits range from 3 TeV to 6 TeV depending on the details of the interaction postulated.

6. Summary

Currently, proton-antiproton collisions afford the opportunity to study parton interactions at the highest energies available. Superficially the descriptions of the processes using QCD, and incorporating parton distribution functions as measured in deep inelastic scattering, are remarkably successful. This is true over a very broad range in transverse momentum and over a broad range of the fractional momentum of the nucleon carried by the participant partons.

However there are two notes of caution.

- When deviations from the prescription provided by the convolution of the parton distribution functions, as measured in deep inelastic scattering, and the hard cross section, as calculated by QCD, occur, the base is not sufficiently firm to claim new physics. Thus far, whenever an apparent deviation has been observed, it has been possible to modify the parton distributions without generating major disagreements with the deep inelastic data.
- It is usually stated that, as the mass scales of the participant partons increases, QCD will give a better description of the data. In fact we see that jets in general, which are dominated by either light quarks or gluons can be described adequately. We also see the t -quark predictions working well. But, in the case of the b quark, agreement is only satisfactory at high p_T ; at low p_T there is disagreement between data and prediction over a wide range of pseudorapidity.

As mentioned earlier the experiments and the Tevatron collider are being upgraded. We can expect in the near future to see:

- more detailed studies of the behaviour of a bare quark, the top quark.
- clarification of the story about heavy quark production.
- an emphasis on the use of W and Z bosons for QCD studies, approximately 10^6 of the former and 10^5 of the latter will be detected.
- deeper probes of potential substructure of the partons.

- extended low x studies with both experiments equipped with small angle detectors.

I would like to acknowledge the efforts of all the collaborators in the two Tevatron Collider collaborations, CDF and DØ. In particular I benefited from discussions with Iain Bertram, Bob Hirosky, Arthur Maciel, Harry Weerts and John Womersley. Finally I would like to thank the organizers for giving me the opportunity to participate in the discussion meeting at such an august institution.

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